Pion Scattering Measurements

Jake Calcutt

NuSTEC Pion Workshop

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MICHIGAN STATE UNIVERSITY

Outline

Motivation

Pion - Nucleus Interactions

DUET

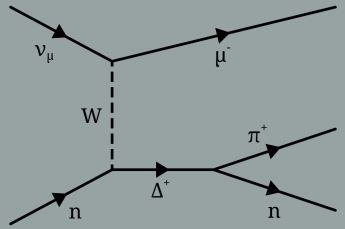
- **For T2K**
- **For NOvA**

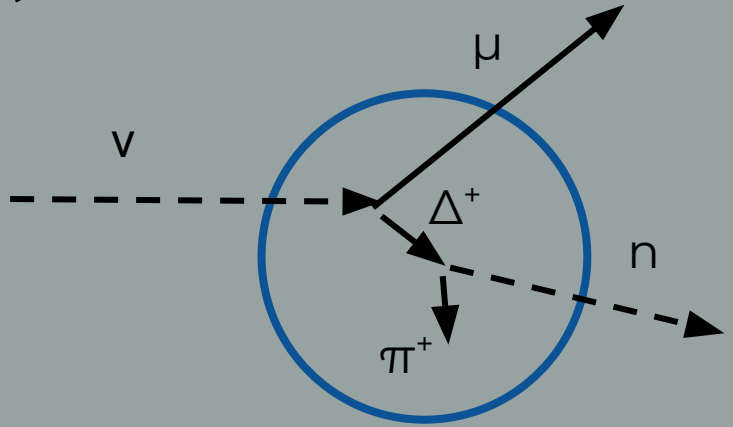
LArIAT

ProtoDUNE-SP

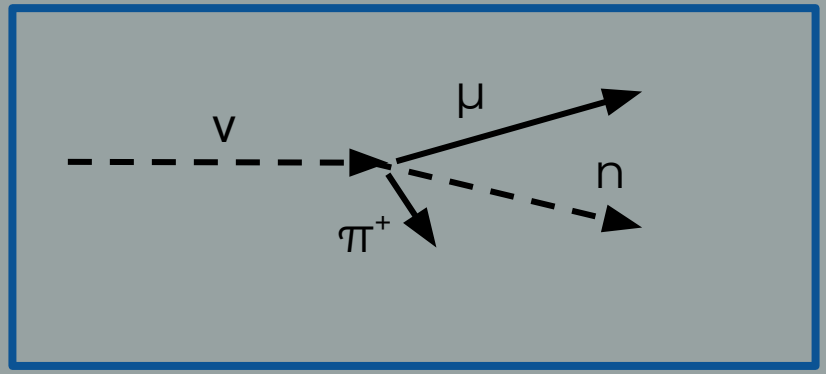
Outlook (Feed into discussion)

Why Measure Pion Scattering?



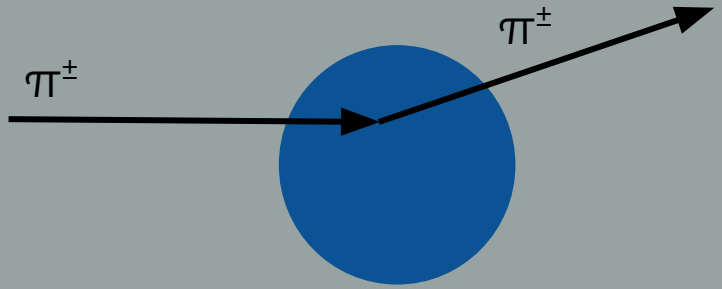


Pion Absorbed in Nucleus
Final State Interactions (**FSI**)

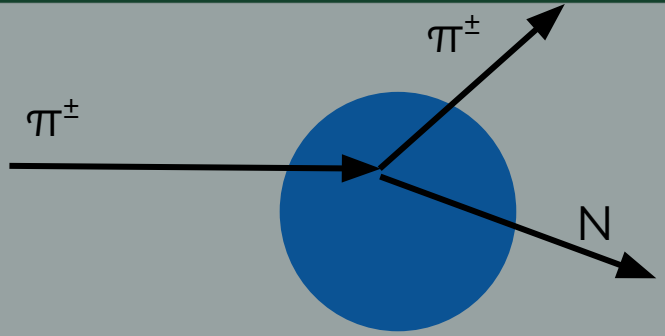


Pion Absorbed in Detector
Secondary Interactions (**SI**)

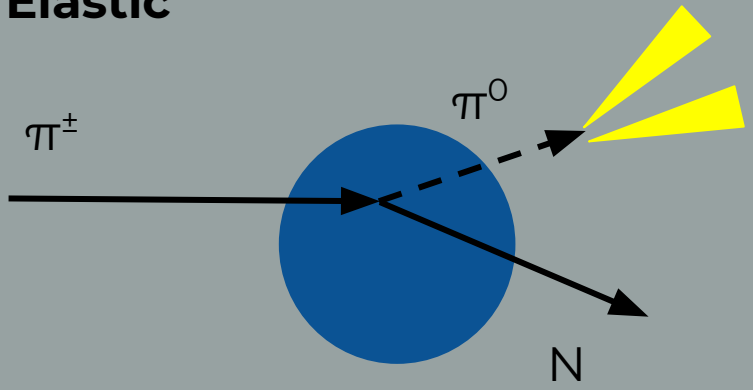
π-Nucleus Interactions



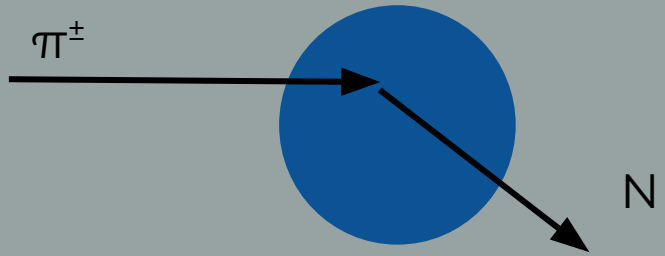
Elastic



Inelastic/Quasi-elastic



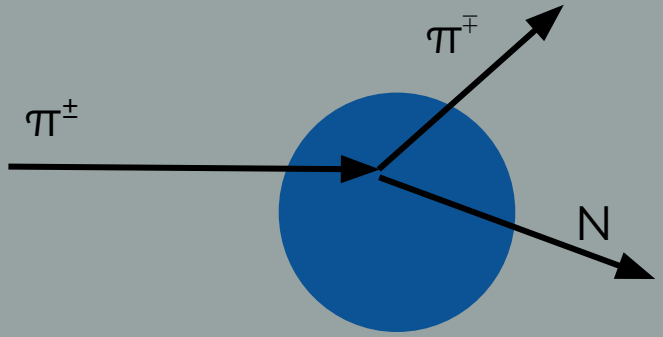
Charge Exchange



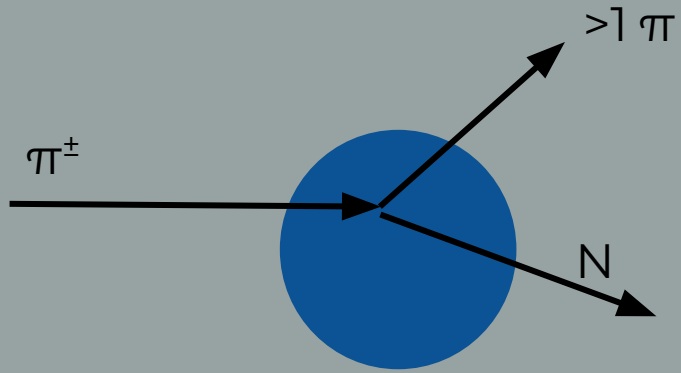
Absorption

N -- Nucleons + Nuclear Fragments

π-Nucleus Interactions



Double Charge Exchange

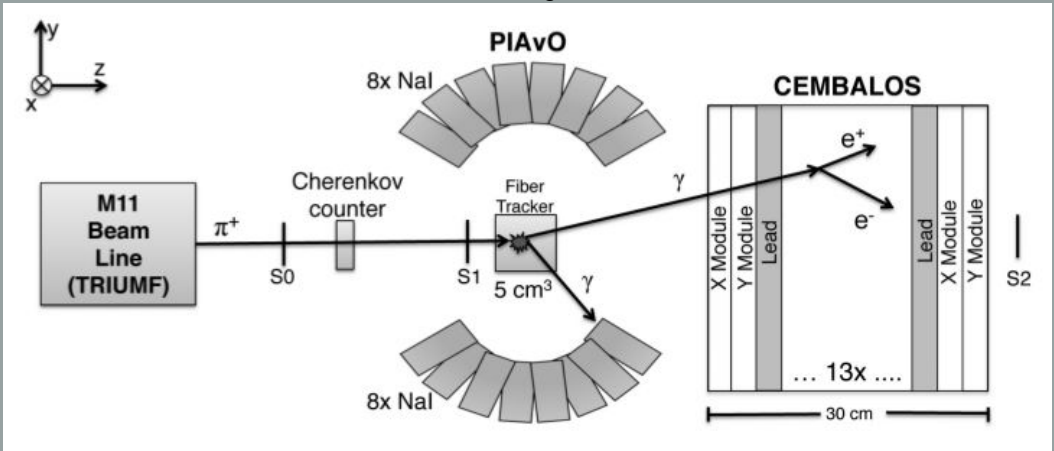


Pion Production

N -- Nucleons + Nuclear Fragments

Dual Use Experiment at TRIUMF -- DUET

Pinzon Guerra et. al, Phys. Rev. C 95, 045203 , 2017



π^+ - Carbon scattering experiment at TRIUMF

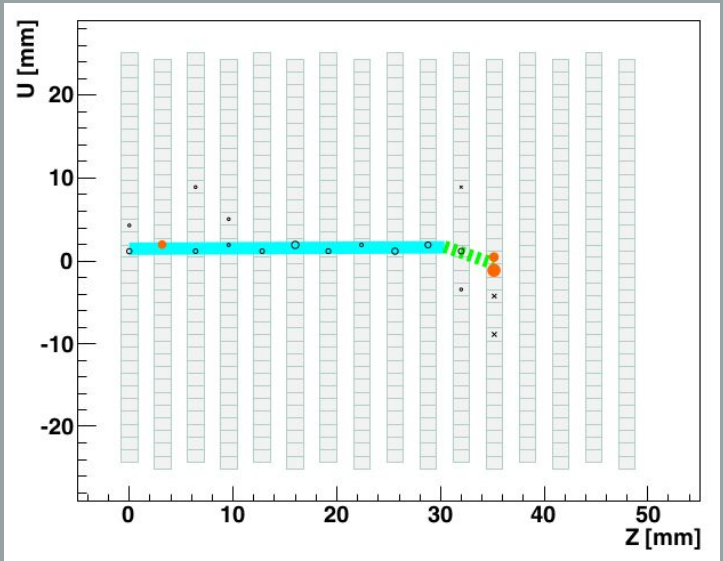
Scintillating fibers used as target + tracking (PIAvO)

Scintillating fibers used for EM showers (CEMBALOS)

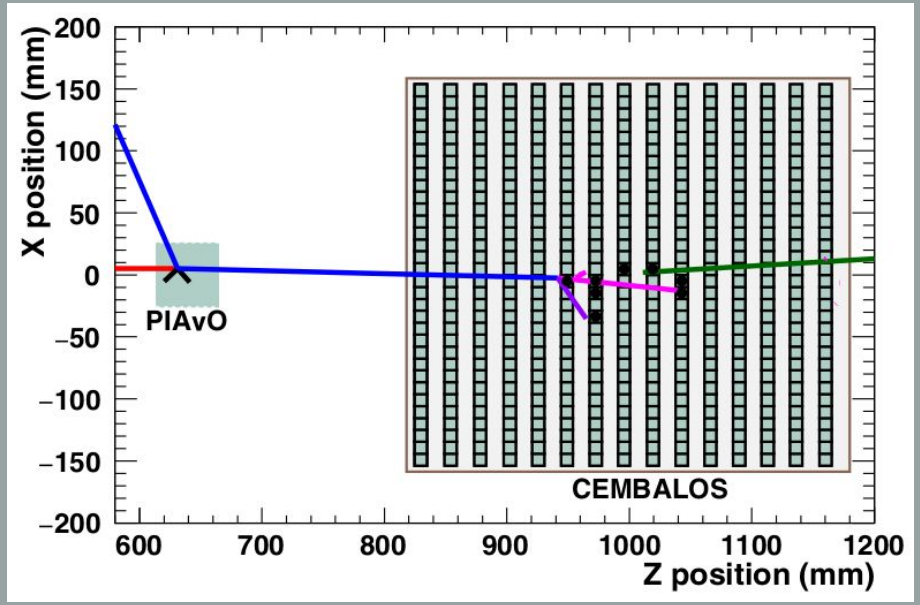
Measured Absorption & Charge Exchange (Combined + Separate)

DUET -- Cross Section

Ieki et. al, Phys. Rev. C 92, 035205, 2015



Pinzon Guerra et. al, Phys. Rev. C 95, 045203 , 2017



Abs+CX: Select any π interaction with no charged π in finall state

CX: Require photon in CEMBALOS

DUET -- Cross Section Extraction

Ieki et. al, Phys. Rev. C 92, 035205, 2015

$$\sigma_{\mathrm{ABS+CX}} = \sigma^{pred}_{\mathrm{ABS+CX}} \times \frac{N_{\mathrm{data}} - N^{pred}_{\mathrm{BG}}}{N^{pred}_{\mathrm{sig}}} \times \frac{1 - R^{data}_{\mathrm{TiO}}}{1 - R^{\mathrm{MC}}_{\mathrm{TiO}}} \times \frac{1}{1 - f_{\mu}}$$

Pinzon Guerra et. al, Phys. Rev. C 95, 045203 , 2017

$$\sigma_{\mathrm{CX}} = \sigma^{\mathrm{MC}}_{\mathrm{CX}} \times \frac{N_{\mathrm{Data}} - N^{\mathrm{MC}}_{\mathrm{BG}}}{N^{\mathrm{MC}}_{\mathrm{CX}}} \times \frac{1 - R^{\mathrm{Data}}_{\mathrm{TiO_2}}}{1 - R^{\mathrm{MC}}_{\mathrm{TiO_2}}} \times \frac{1}{1 - f_{\mu}}. \quad (2)$$

σ_{ABS} was obtained by subtracting σ_{CX} from $\sigma_{\mathrm{ABS+CX}}$ obtained in Ref. [25].

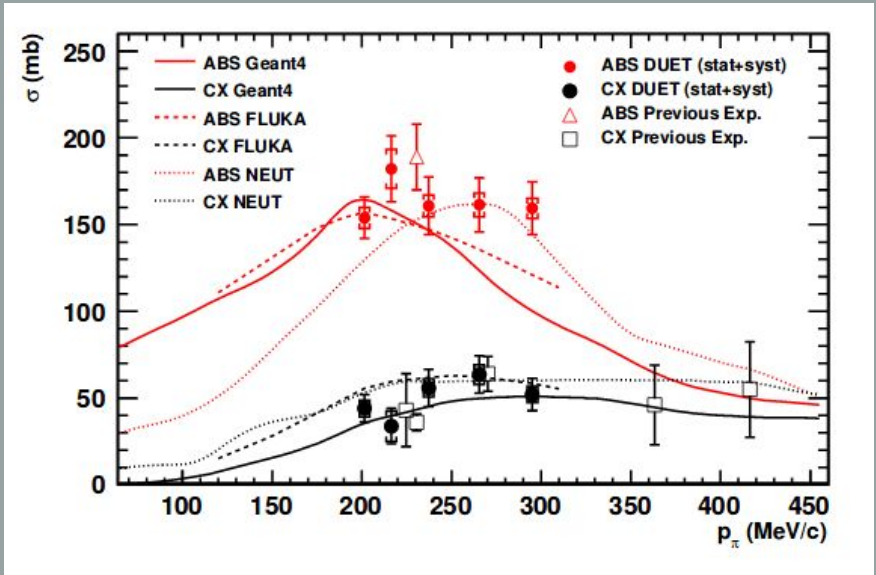
Used selected events to scale the Geant4 cross section

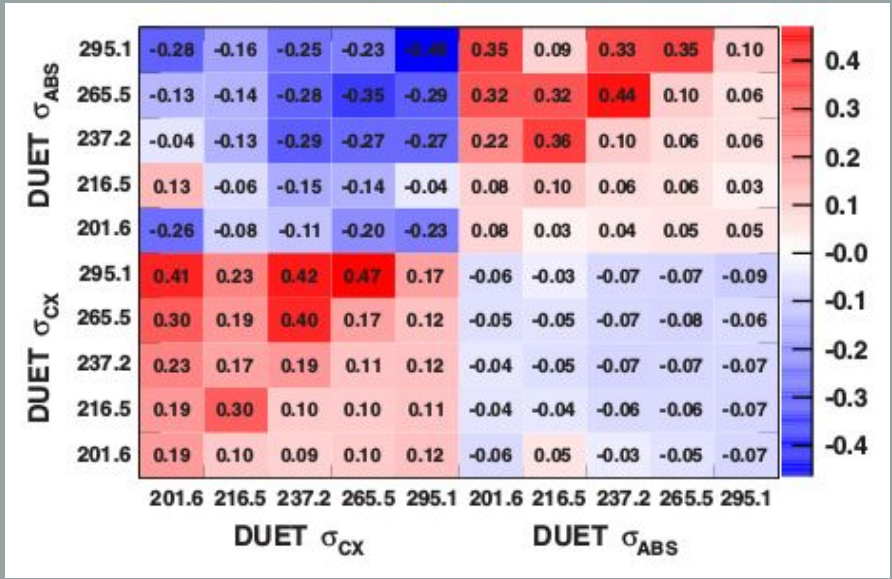
Correct for background muons (f_{μ})

Correct for interactions on fiber coatings (R^{x}_{TiO})

DUET Results

Pinzon Guerra et. al, Phys. Rev. C 95, 045203 , 2017





Measured Absorption & Charge Exchange (Combined + **Separate**)

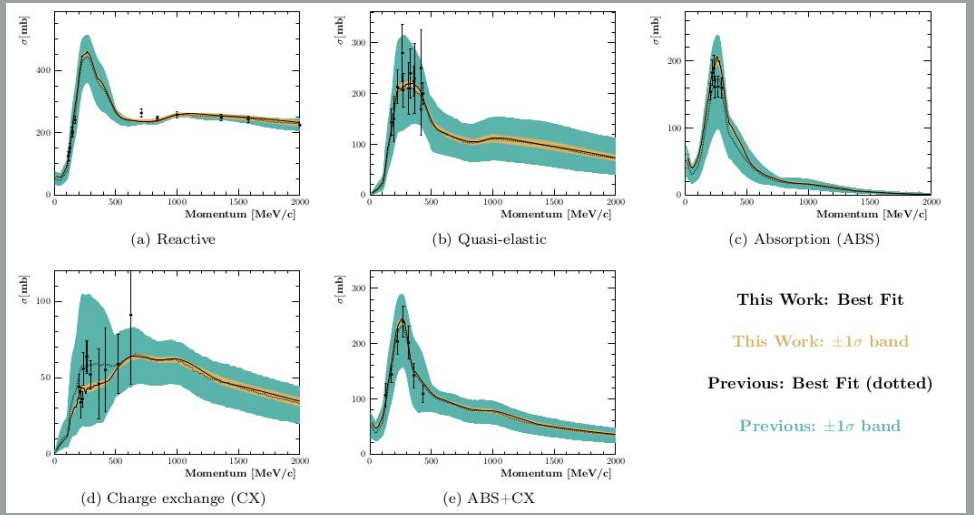
Improvement over past measurements: Published covariance

DUET Use in T2K

T2K uses **NEUT** for their neutrino interaction modelling

- Set of **tunable parameters** controlling **$\pi^{\pm}$ - FSI** in the cascade
- π - scattering routine used to **compare to external data** on multiple nuclei (including **DUET**)

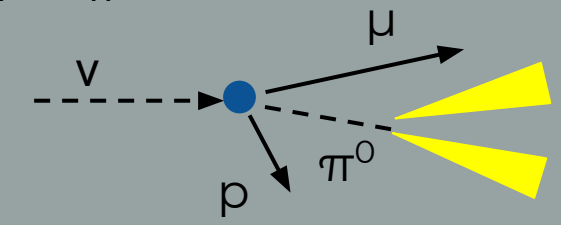
Resulted in a tune for NEUT's cascade model

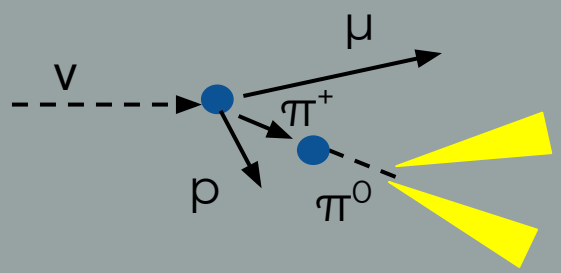


Pinzon Guerra et. al, Phys. Rev. D 99, 052007 2019

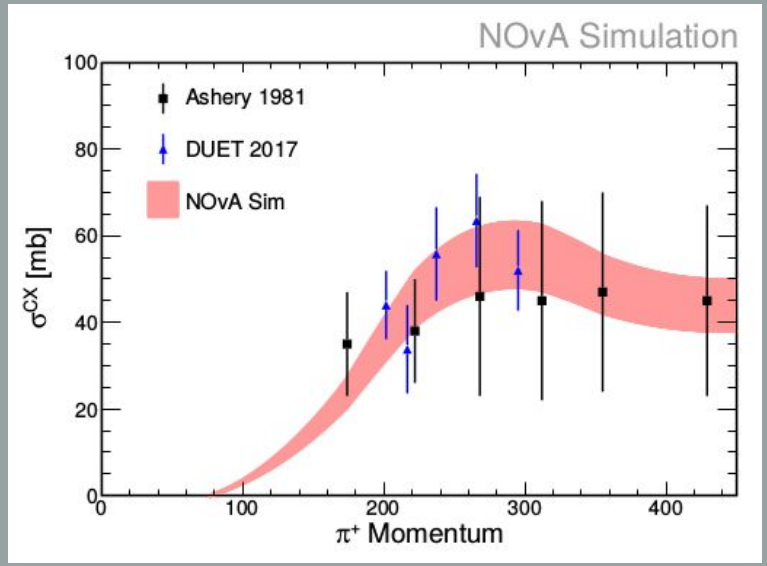
DUET Use in NOvA

Background to CC1π^0 measurement includes CC1π^+ with $\pi^+ \rightarrow \pi^0$





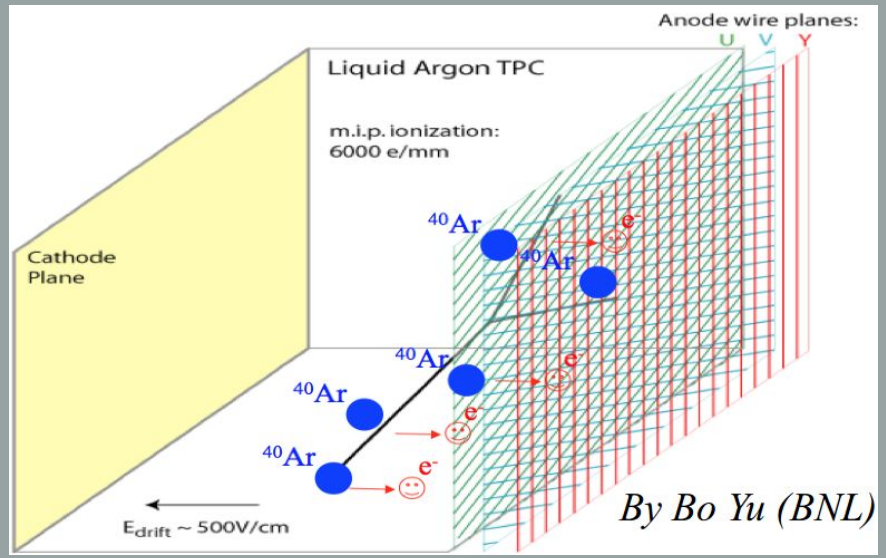
Used DUET charge exchange data to constrain this

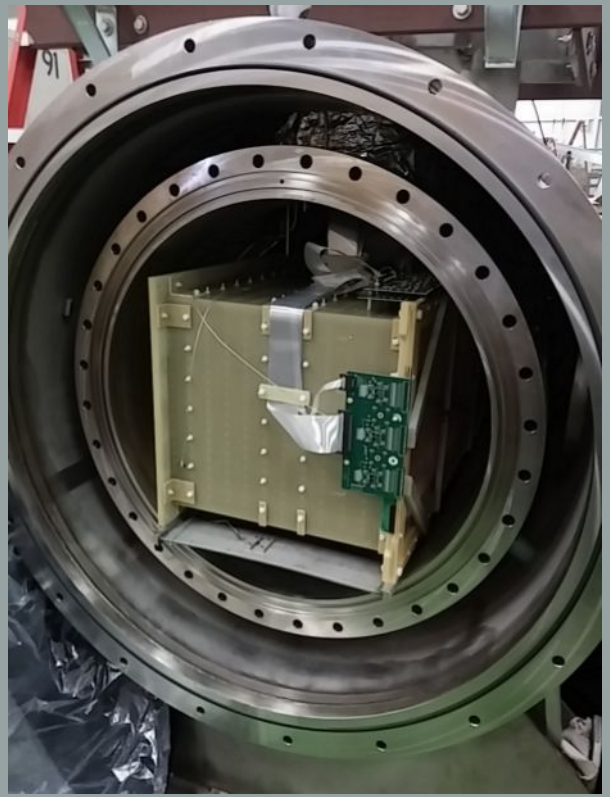


Thesis, Dan Pershey, Caltech 2018

Liquid Argon In A Testbeam -- LArIAT

Repurposed Argoneut TPC placed in a testbeam at FNAL

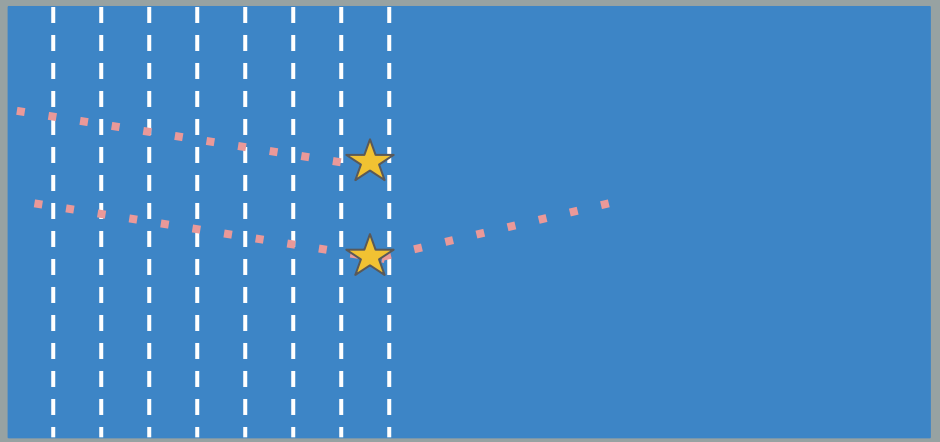




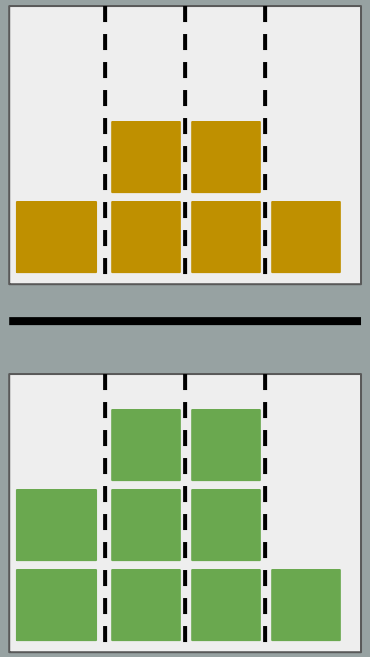
Thesis, Elena Gramellini, Yale 2018

LArTPC Cross Sections -- Thin Slices

- Estimate the energy at each slice (using calorimetry info)
  - Fill the **Incident** histogram (bottom) for each slice's energy
- Determine interaction point
  - Passes signal selection?
    - Fill **Interacting** (top) histogram



$\sigma \sim$

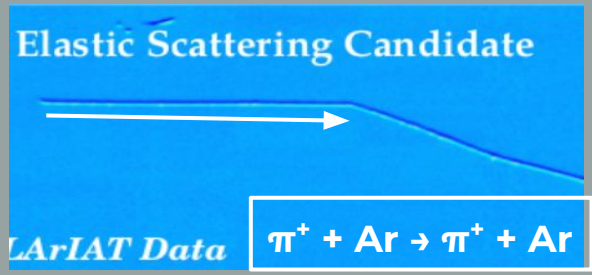


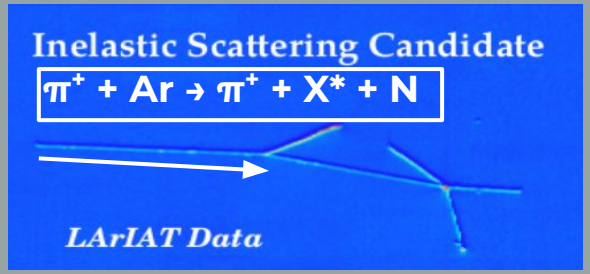
Kinetic Energy

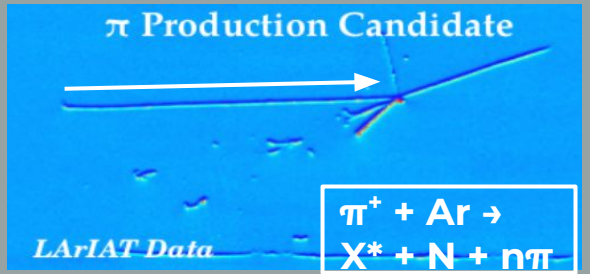
LArIAT Selection

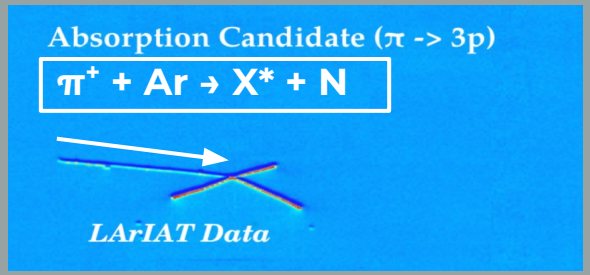
Recent thesis results (next page) for total $\pi^{\pm}$ - Ar σ

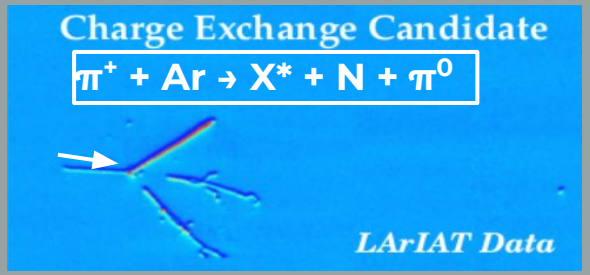
Note: Inefficiency for reconstructing low-angle scatters (< 5°)











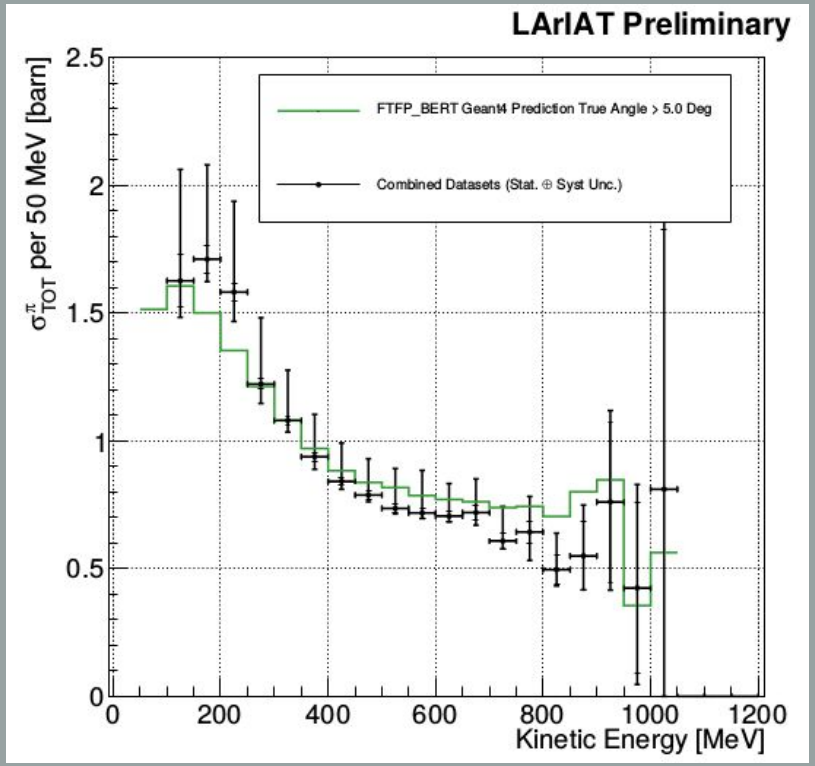
Thesis, Elena Gramellini, Yale 2018

Inelastic includes DCEX

LArIAT Results (Preliminary)

Disagreement in the negative π cross section with Geant4 at high energies and in resonance region

LArIAT notes this is could be due to a (possibly unknown) systematic uncertainty

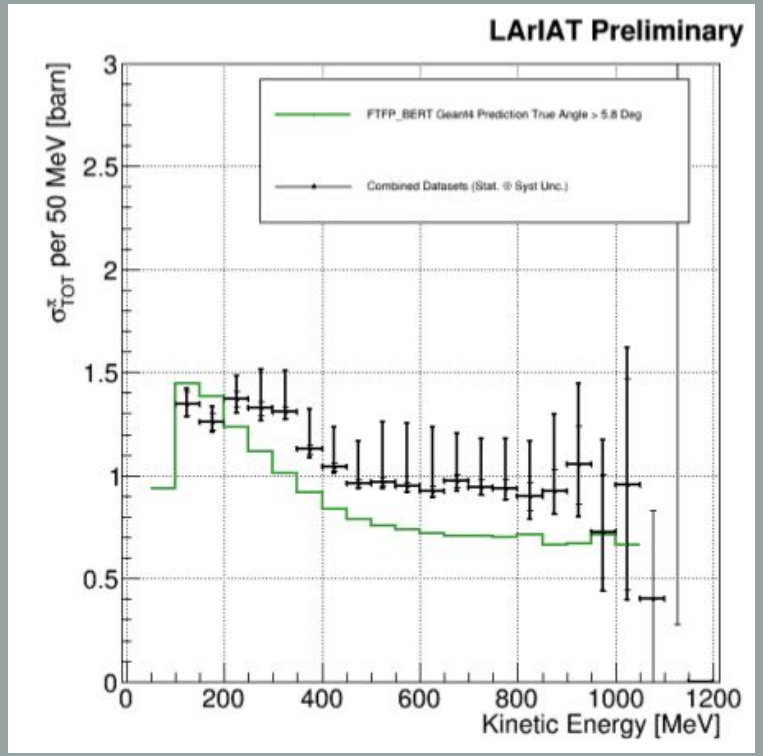


Thesis, Elena Gramellini, Yale 2018

LArIAT Results (Preliminary)

Disagreement in the positive π cross section with Geant4 as well

Noted in the thesis that this could be due to a misunderstanding of the beam composition or other systematic



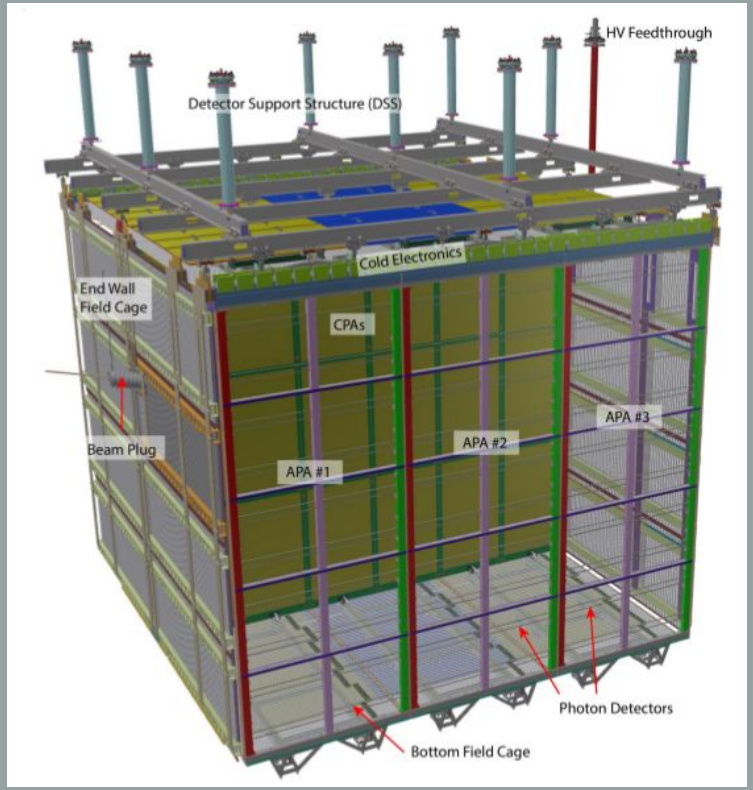
Thesis, Gregory Pulliam, Syracuse 2019

ProtoDUNE -- Single Phase

400T FV LArTPC operating in a testbeam at CERN

Took beam data Oct. - Nov. 2018

Proposed 2nd run in 2021 (after CERN's Long Shutdown 2)



Abi, B. et al., The Single-Phase ProtoDUNE Technical Design Report, 2017, Fermilab-Design-2017-02

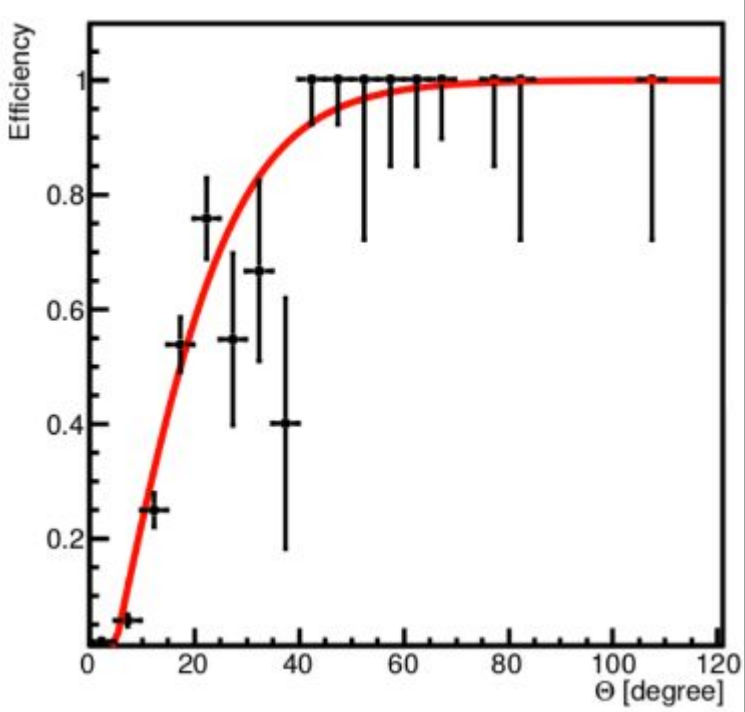
ProtoDUNE -- Current Analysis Work

Total Cross Section

Challenge: reconstructing low-angle scatters (similar to LArIAT)

Right: vertex identification efficiency for protons (similar to pions)

Work ongoing to develop/improve alternate vertex reconstruction



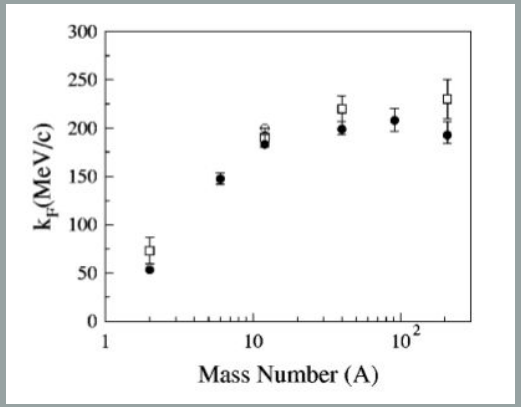
Heng-Ye Liao, DUNE Collaboration Meeting, May 2019

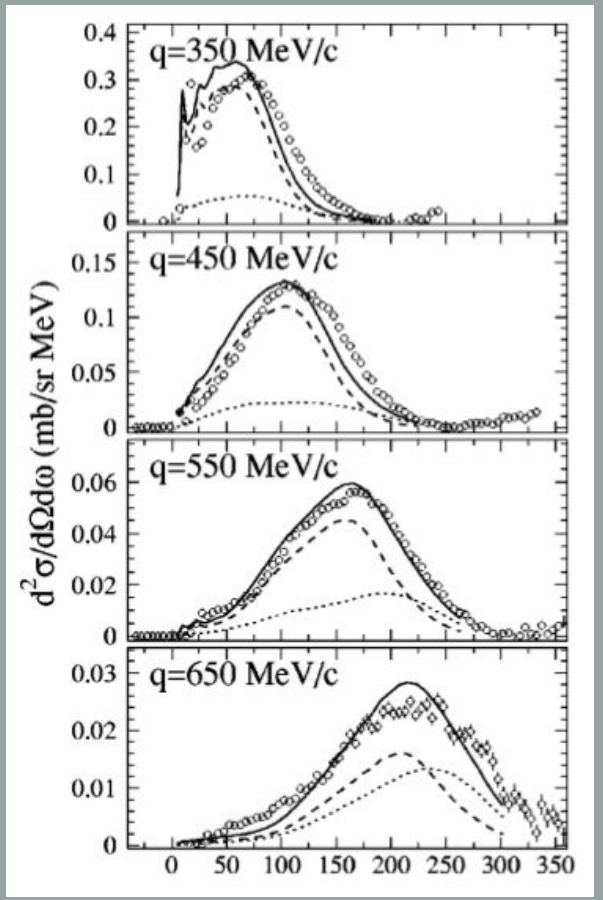
ProtoDUNE -- Current Analysis Work

Quasi-Elastic Scattering

Talk given at Sep. ‘19 DUNE CM trying to convince someone to take up this analysis for useful model constraints.

Motivated by a measurement from KEK: *PRC 64, 034608 (2001)*.





ProtoDUNE -- Current Analysis Work

Combined Absorption + Charge Exchange (my work)

Abs. can probe NN + multinucleon (per Jerry Miller's talk)

Signal: no charged pions in final state (proton-like tracks ok)

Need to redefine/refine measurement?

- Not sensitive to multiple π^0 (small fraction) and below-threshold $\pi^{\pm}$
- What is good for theorists/model builders? (Discussion)

ProtoDUNE -- Current Analysis Work

Separate Absorption + Charge Exchange

Extension on previous slide. Requires good ability on identifying π^0 showers, then get the separate cross sections ‘for free’

Can then categorize the absorption events by proton multiplicity

Neutrons could be difficult to tag -- possibly preventing any categorization by neutron multiplicity

Future Measurements (ProtoDUNE)

What do theorists/model builders want?

Thanks For Listening

Backup Slides

Cascade Models

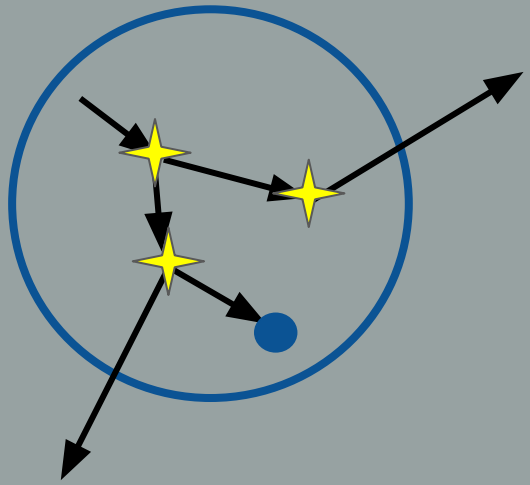
Neutrino event generators and **particle transport simulations**

Hadrons take a series of steps throughout the nucleus

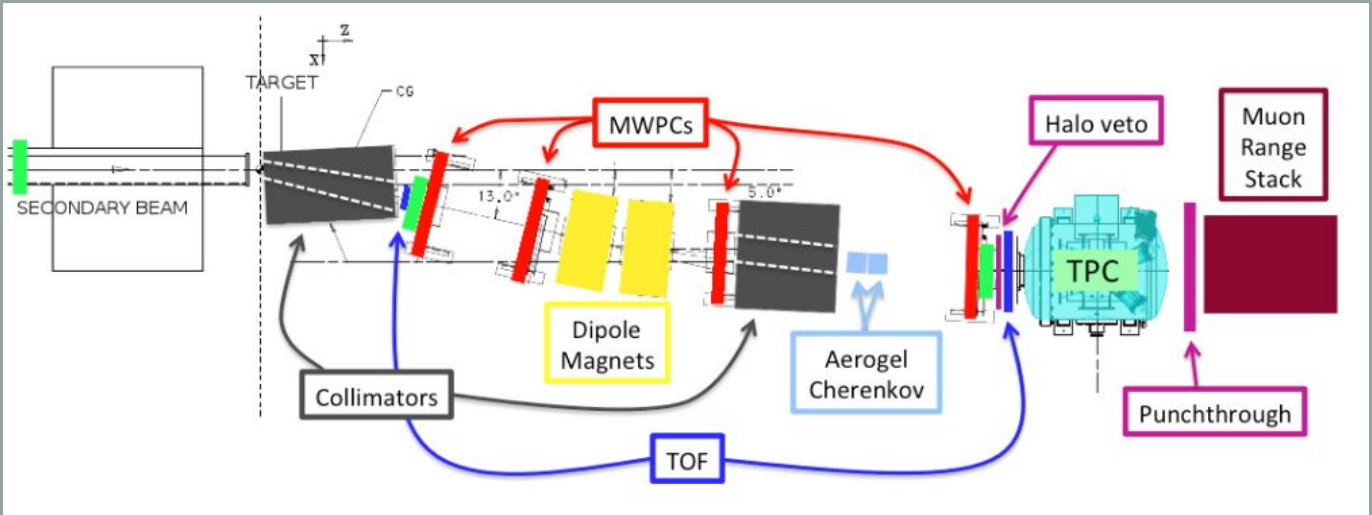
- Possibility of interaction

Interaction occurs: the products are **added to the ‘stack’** of active particles

Process repeats until all active particles are **absorbed** or l**eave nucleus**

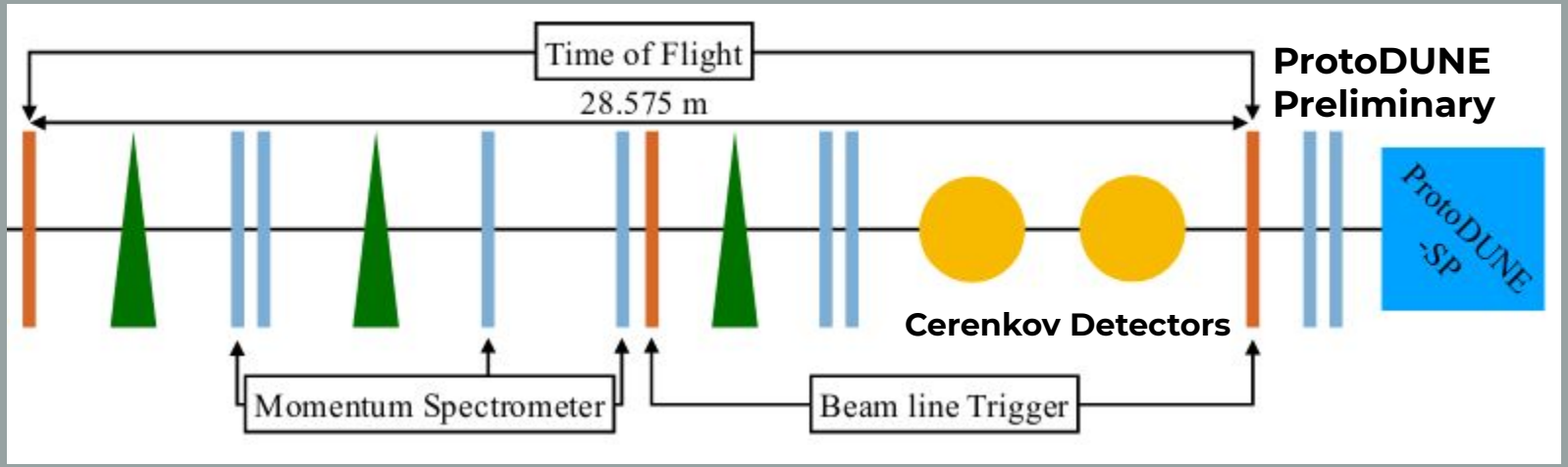


LArIAT Beamline



Thesis, Elena Gramellini, Yale 2018

ProtoDUNE Beamline



ProtoDUNE Beam Run + Stats

Beam Momentum (GeV/c)	Estimated Pi-Like Beam Triggers
0.5	1.5 k
1	381 k
2	333 k
3	284 k
6	394 k
7	343 k

GeantReweight

GeantReweight

Package to handle **systematics** related to **pion scattering** by:

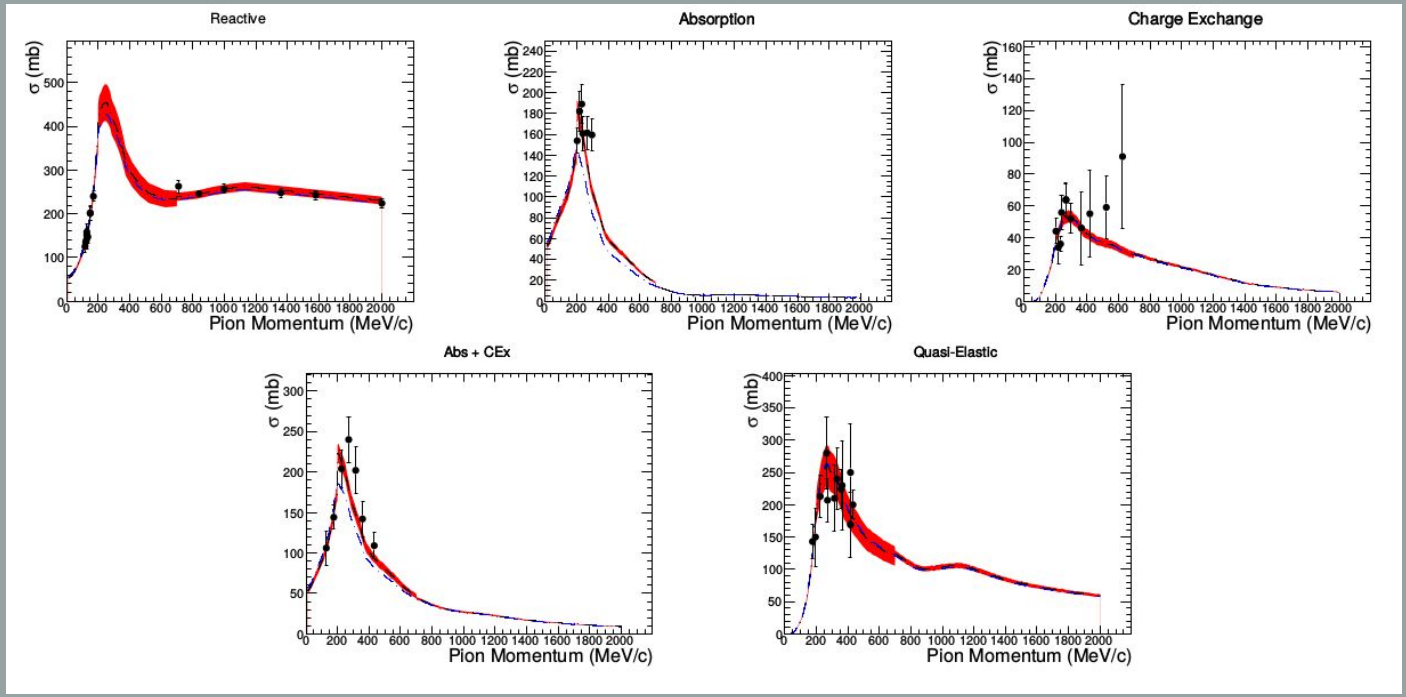
1. **Fitting** Geant4 predictions to external data
2. **Reweighting** Geant4 tracks given some variation to the interaction cross sections

https://cdcvs.fnal.gov/redmine/projects/geant4reweight/

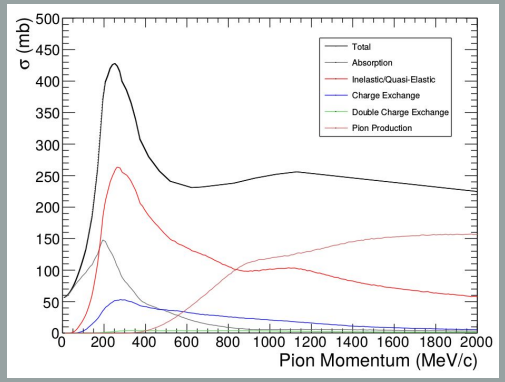
GeantReweight

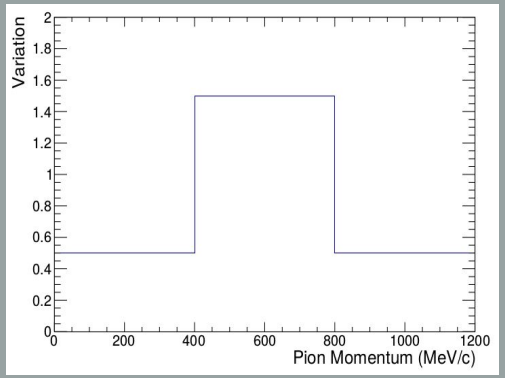
Example fits: π^+ -- C scattering

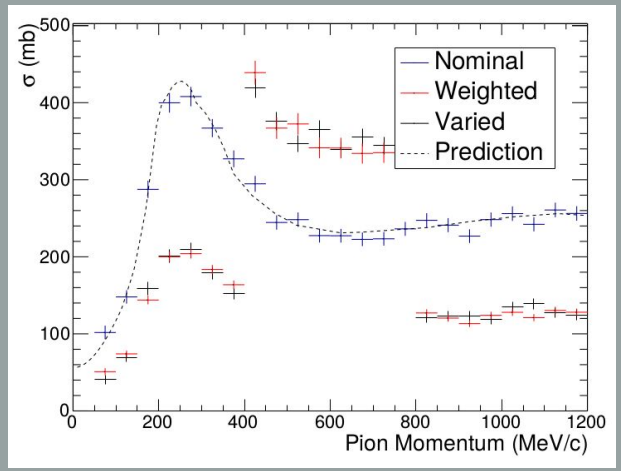
Fit parameters are binned variations which scale the cross sections



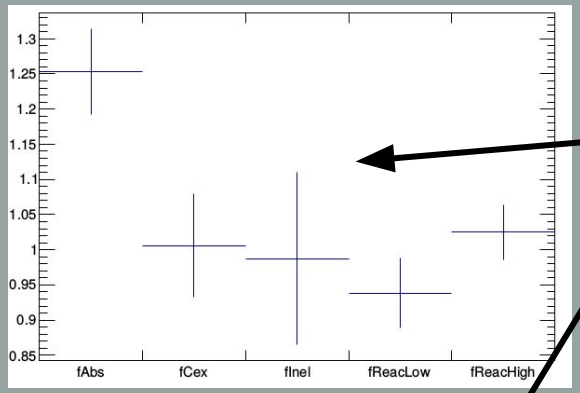
GeantReweight



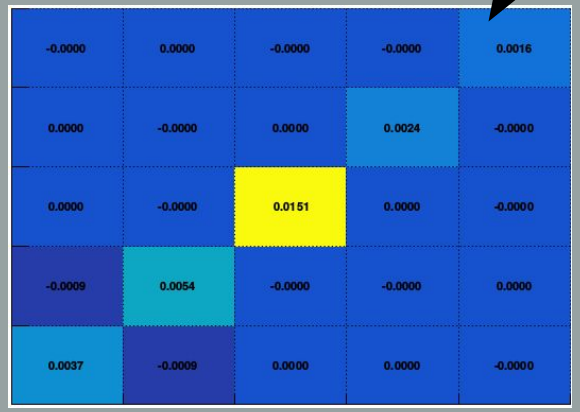


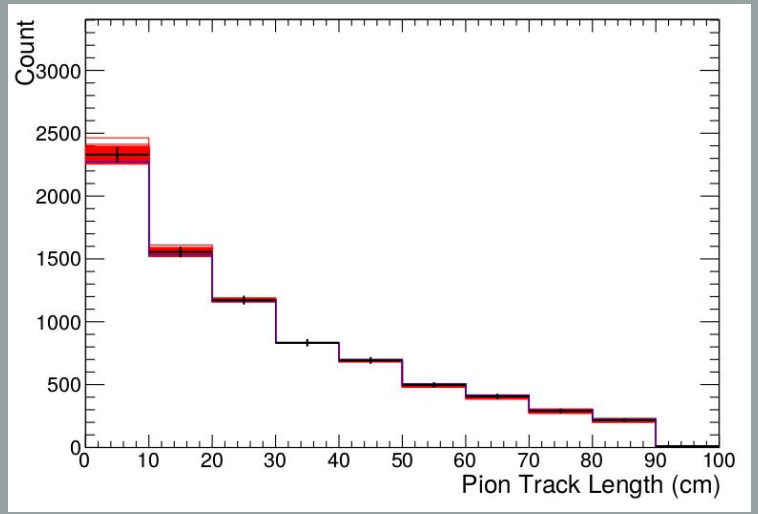


GeantReweight



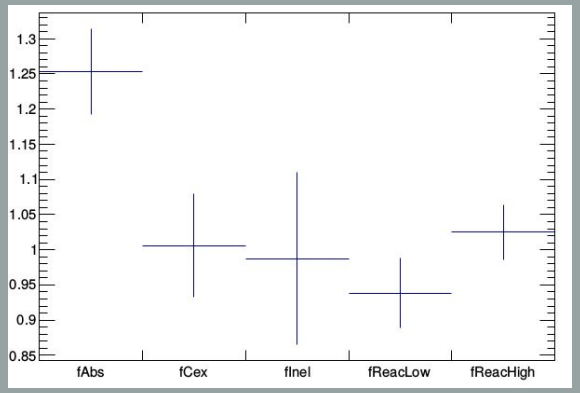
Construct sets of variations (i.e. “toy experiments”, “many universes”) using fit results



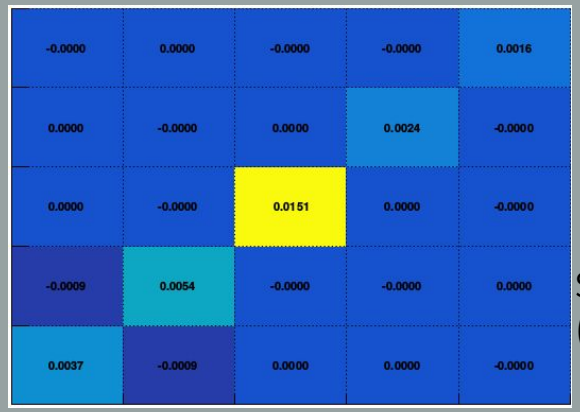


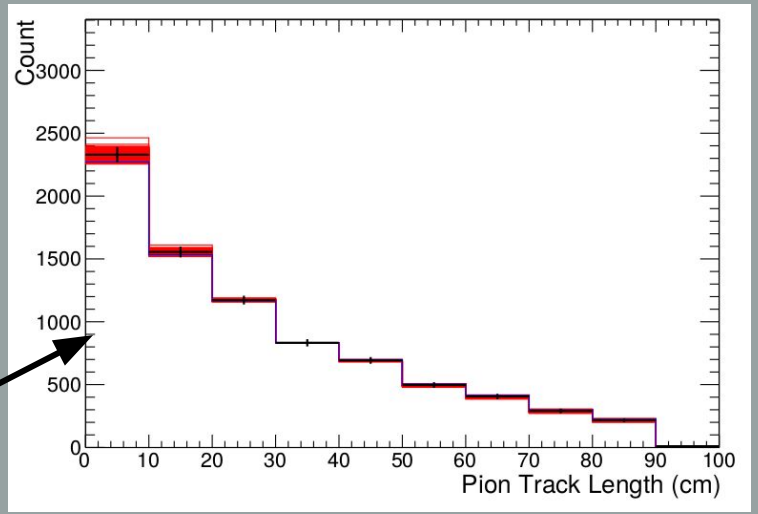
GeantReweight

Jake Calcutt



Create variations from throws and use in reweighting





See effect on observables (Simple case)

GeantReweight

Consider a variation to the inelastic cross cross section: $\sigma \rightarrow \sigma'$

Within a track: the pion takes steps with a change of udnergoing an Inelastic interaction each step

- Real process choice is relatively complicated
- But for these purposes, can be approximated as

a) $P_{\text{no inter}} \sim e^{-L\sigma}$ **b)** $P_{\text{inter}} \sim 1 - e^{-L\sigma}$

If a pion track ends without an inelastic interaction (i.e it leaves the tracking region, or undergoes a different process, etc.) assign weights for all steps of form **a**

$$W_{surv} = \frac{e^{-\sum_{i=1}^{N} \sigma_i' L_i}}{e^{-\sum_{i=1}^{N} \sigma_i L_i}}$$

GeantReweight

Consider a variation to the inelastic cross cross section: $\sigma \rightarrow \sigma'$

Within a track: the pion takes steps with a change of udnergoing an Inelastic interaction each step

- Real process choice is relatively complicated
- But for these purposes, can be approximated as

a) $P_{\text{no inter}} \sim e^{-L\sigma}$ **b)** $P_{\text{inter}} \sim 1 - e^{-L\sigma}$

If a pion track ends with an inelastic interaction, assign weights for all steps before the last of form **a**, replace last with **b**

$$W_{int} = \left(\frac{1 - e^{-\sigma'_N L_N}}{1 - e^{-\sigma_N L_N}}\right)\left(\frac{e^{-\sum_{i=1}^{N-1} \sigma'_i L_i}}{e^{-\sum_{i=1}^{N-1} \sigma_i L_i}}\right)$$